ESTCP
Cost and Performance Report

(MR-201231)

Quality Control Methodologies for Advanced EMI Sensor Data Acquisition and Anomaly Classification

September 2017

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14. ABSTRACT

This report details a live site demonstration project conducted by WESTON at Southwest Proving Ground, Arkansas and Andersen Air Force Base, Guam as part of Environmental Security Technology Certification Program (ESTCP) Munitions Response Project MR-201231. The purpose of the project was to demonstrate the effectiveness of the advanced sensor and classification methodology for identifying targets of interest (TOIs) at a military construction (MILCON) site potentially containing a diversity of munitions. At Southwest Proving Ground, 11.23 acres of dynamic detection surveys were conducted using the MetalMapper advanced electromagnetic induction (EMI) sensor. A total of 2,116 anomalies were selected from the dynamic data for cued investigation. The classification methodology resulted in the correct classification of 100% of TOI and yielded a reduction in clutter digs of 83%. At Andersen Air Force Base, 2.97 acres of dynamic detection surveys were conducted using TEMTADS 2x2 advanced electromagnetic induction (EMI) sensor. A total of 1,195 anomalies were selected from the dynamic data for cued investigation. The classification methodology resulted in the correct classification of 100% of TOI and yielded a reduction in clutter digs of 81%.

15. SUBJECT TERMS

MetalMapper, TEMTADS, UXO, MEC, Guam, geophysical classification, MMRP, ESTCP, MILCON

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ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
AGC	advanced geophysical classification
cm	centimeter(s)
EM	electromagnetic
EMI	electromagnetic induction
ESTCP	Environmental Security Technology Certification Program
GPS	global positioning system
IMU	inertial measurement unit
ISO	Industry Standard Object
IVS	instrument verification strip
m	meter(s)
m^2	square meter
MEC	munitions and explosives of concern
MILCON	military construction
mm	millimeter
MMRP	Military Munitions Response Program
MRS	Munitions Response Site
NRL	Naval Research Laboratory
NRP	North Ramp Parking
RMS	root mean square
RTK	Real Time Kinematic
QC	quality control
SERDP	Strategic Environmental Research and Development Program
SWPG	Southwestern Proving Ground
TOI	target of interest
UXO	unexploded ordnance

EXECUTIVE SUMMARY

Weston Solutions, Inc. performed two Environmental Security Technology Certification Program (ESTCP) Live Site Demonstrations of advanced geophysical classification (AGC) technologies at Southwestern Proving Ground (SWPG), Arkansas, and Andersen Air Force Base (AFB), Guam. Detailed information about each demonstration is contained in their respective Final Reports published on the ESTCP website. This document is intended to summarize the demonstrations at each of these sites and assess the performance and cost benefits of implementing AGC technologies.

OBJECTIVES OF THE DEMONSTRATION

The demonstrations were designed to validate the effectiveness of the advanced sensors and classification methodology at these sites containing a diversity of munitions, densities, and physical challenges.

The primary objectives of each individual Live Site Demonstration were to do the following:

- Correctly classify all targets of interest (TOIs).
- Correctly identify TOI and non-TOI sizes.
- Correctly estimate extrinsic parameters (measured location and depths of items).
- Reduce clutter digs by at least 50%.
- Extract reliable parameters for at least 95% of cued anomalies.
- Demonstrate the cost benefit and performance of these sensors and methods.

TECHNOLOGY DESCRIPTION

These demonstrations consisted of dynamic and cued data collection with the MetalMapper and TEMTADS 2x2 advanced geophysical sensor systems. Analysis of the data was performed using conventional and advanced data processing methods to select anomalies from the advanced sensor dynamic detection data, and then extract features and perform anomaly classification on the advanced sensor cued data.

DEMONSTRATION RESULTS

SWPG: Weston conducted the field demonstration in three phases with 4–6 weeks between each phase to perform data processing and classification. The initial phase included site setup, surface sweep, production area seeding, and dynamic data collection of the survey area. A total of 43 seeds were installed, and 11.23 acres of dynamic surveys were performed with the MetalMapper system. A total of 2,116 targets were selected from the dynamic data for cued investigation, which was performed during the second phase. Weston returned to SWPG for the final intrusive phase, during which 1,398 targets were intrusively investigated. The classification methodology resulted in the correct classification of 100% of TOI, and yielded a reduction in clutter digs of 83%.

Andersen AFB: The demonstration was integrated with an ongoing munitions and explosives of concern (MEC) removal action project being performed in advance of military construction (MILCON) activities. Dynamic detection surveys using TEMTADS 2x2 were performed across 2.97 acres of the site following a traditional EM61-MK2 Metal Detector survey. A total of 970 targets were selected from the TEMTADS 2x2 dynamic survey data. An additional 225 targets were selected from EM61-MK2 data that did not overlap with the TEMTADS 2x2 survey. Each of the 1,195 anomalies were reacquired and interrogated using cued data collection with the TEMTADS 2x2. All TOI were correctly identified during the demonstration. The classification process resulted in correctly identifying 100% of TOI and reduced the number of clutter or non-munitions-related material that would require investigation by 81%.

IMPLEMENTATION ISSUES

Continual assessments on these advanced sensor technologies at demonstration sites is imperative to the continued development of the instruments. This report will discuss implementation issues related to equipment shipping, weatherproofing, configurations, structural improvements, and potential modifications observed during these demonstrations. These implementation issues are documented and discussed to continually assist in the development of a more market-ready equipment, and to facilitate the understanding and acceptance of advanced geophysical sensors to improve deployment efficiency.

1.0 INTRODUCTION

1.1 BACKGROUND

Weston Solutions, Inc. performed an Environmental Security Technology Certification Program (ESTCP) Live Sites Demonstration of advanced geophysical classification (AGC) sensor technologies at two project locations: Southwestern Proving Ground (SWPG), Arkansas, and Andersen Air Force Base (AFB), Guam. Detailed information regarding each site location, survey design, and technology results is contained in respective Final Reports published on the Strategic Environmental Research and Development Program (SERDP)/ ESTCP website.

1.2 OBJECTIVE OF THE DEMONSTRATION

It is the goal of ESTCP to utilize AGC to increase efficiency of the Military Munitions Response Program (MMRP) and reduce costs associated with intrusive investigations of harmless metallic objects (e.g., range-related debris, or cultural debris). The demonstrations referred to in this report were designed to validate the effectiveness of the advanced sensors and classification methodology at these sites containing a diversity of munitions, densities, and physical challenges.

The primary objectives of each individual demonstration of AGC activities were to do the following:

- Correctly classify all targets of interest (TOIs).
- Correctly identify TOI and non-TOI sizes.
- Correctly estimate extrinsic parameters (measured location and depths of items).
- Reduce clutter digs by at least 50%.
- Extract reliable parameters for at least 95% of cued anomalies.
- Demonstrate the cost benefits and performance of these sensors and methods.

1.3 REGULATORY DRIVERS

The MMRP is charged with characterizing and, where necessary, remediating Munitions Response Sites (MRSs). When an MRS is remediated, it is typically mapped with a geophysical system, based on either a magnetometer or an electromagnetic induction (EMI) sensor, and the locations of all detectable signals are excavated. Many of these detections do not correspond to munitions, but rather to harmless metallic objects or geologic features. Field experience indicates that often in excess of 90% of objects excavated during the course of a munitions response are found to be nonhazardous items. Current geophysical technology, as it is traditionally implemented, does not provide a physics-based, quantitative, validated means to discriminate between hazardous munitions and nonhazardous items.

With no information to suggest the origin of the signals, all anomalies are currently treated as though they are intact munitions when they are dug. They are carefully excavated by unexploded ordnance (UXO) technicians using a process that often requires expensive safety measures, such as barriers or exclusion zones. As a result, most of the costs to remediate an MRS are currently spent on excavating targets that pose no threat. If these items could be determined with high confidence to be nonhazardous, some of these expensive measures could be eliminated or the items could be left unexcavated entirely.

2.0 TECHNOLOGY

AGC technologies and methodologies utilized for each demonstration is summarized in Table 2.1.

Table 2.1. Classification Technology Used at the Demonstration Sites

Demonstrated Technology	Southwestern Proving Ground (SWPG)	Andersen AFB
Geophysical Survey	MetalMapper in a towed configuration for dynamic and cued surveys.	TEMTADS 2x2 in a person-portable cart configuration for dynamic and cued surveys.
Software for Data Analysis	Geosoft Oasis montaj UX-Analyze extension.	
Analysis Methods	Library matching and cluster analysis.	
Analysis Categories	Category 0: Cannot Analyze Category 1: Likely TOI Category 2: Cannot Decide Category 3: Likely Non-TOI	

2.1 TECHNOLOGY DESCRIPTION

2.1.1 Geometrics MetalMapper

The Geometrics MetalMapper is the first commercially available advanced EMI sensor designed to enable classification of TOI. It consists of three orthogonal 1-square-meter (m^2) transmit coils and seven 10-centimeter (cm), three-component, orthogonal receiver coils. The system was proven at the ESTCP Live Site Demonstrations at the former Camp San Luis Obispo and other live sites to be effective at discriminating between munitions and non-munitions items. Weston operated the MetalMapper in both dynamic detection and cued interrogation modes during the Live Site Demonstration at SWPG. The MetalMapper provides more accurate target positioning advantages over currently used technologies (e.g., EM61-MK2) because of its seven three-component receivers, greater data density, and improved positioning electronics.

2.1.2 TEMTADS 2X2

The TEMTADS 2x2 is an adaptation of the Naval Research Lab's standard TEMTADS 5x5 element sensor configuration using a smaller 2x2 element array. The TEMTADS 2x2 consists of four 35-cm transmit coils with four 8-cm tri-axial receiver cubes. The receiver cubes are similar in design to those used in the second-generation Advanced Ordnance Locator and the Geometrics MetalMapper system with dimensions of 8 cm rather than 10 cm. It is as reliable as the original TEMTADS, but its portability and smaller size enables access to difficult terrain where mobility is limited. The center-to-center distance between the transmit coils is 40 cm, yielding an 80 cm x 80 cm array. The array is deployed on a set of wheels resulting in a sensor height of approximately 18 cm.

The transmitter electronics and the data acquisition computer are mounted on the operator backpack, and a global positioning system (GPS) antenna and an inertial measurement unit (IMU) are mounted above the center of the TEMTADS 2x2 sensor array. The TEMTADS 2x2 can be operated in two modes: dynamic (or detection) mode and cued mode. Data collection is controlled in dynamic mode using the EM3DAcquire application suite, similar to that used for the Geometrics MetalMapper systems. Custom software written by the Naval Research Laboratory (NRL) is used for cued data acquisition. In cued mode, the locations of previously-identified anomalies are reacquired and flagged prior to being cued with the TEMTADS 2x2.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

2.2.1 MetalMapper

The MetalMapper has a large sensor and bulky components required for its operation (Microsoft Windows computer, monitor, 12-volt batteries); therefore, a deployment vehicle is required during surveys. For this demonstration, a diesel-powered tele-lifter was used for survey activities. The size and portability of the MetalMapper in the open field at SWPG became an issue because of clay-rich soils that were saturated from periodic heavy rains. These field conditions impacted all phases of field operations and likely would have had similar impact on other survey instrumentation.

2.2.2 TEMTADS 2X2

The TEMTADS 2x2 is a man-portable sensor, however, the associated components (tablet, heavy backpack, and batteries) limit the ability of an operator to collect data without assistance from additional personnel. For this demonstration, two personnel were utilized during the data collection: one person to operate/navigate the sensor, and a second to operate the tablet and place navigational aids and monitor the tablet. The TEMTADS 2x2 sensor is also not ruggedized to withstand inclement weather (light rain, snow, etc.). This proved problematic during the Andersen AFB demonstration, as the climate on Guam is hot and humid with frequent precipitation.

2.2.3 AGC Data Processing

Compared to a typical EM61-MK2 survey, the AGC dynamic surveys generated more files that were larger in size, and data processing was time-consuming. The large file sets can be difficult to share data and collaborate with non-local colleagues. The increased processing time made it more time consuming to experiment and discover better ways of handling the data. Weston processed both AGC dynamic and cued data; however, classification of dynamic AGC data is not an option within the commercially available UX-Analyze extension of Geosoft Oasis montaj.

3.0 PERFORMANCE OBJECTIVES

Performance objectives developed during the planning phase for the SWPG and Andersen AFB demonstrations are provided in Table 3.1 and Table 3.2, respectively. The performance objectives serve as a basis for the evaluation of the performance and costs of the demonstrated technologies.

Table 3.1. Quantitative Performance Objectives for SWPG

Performance Objectives	Metric	Success Criteria	Results
Repeatability of Instrument Verification Strip (IVS) measurements	Amplitude of electromagnetic (EM) anomaly Measured target locations	Adv. Sensors Survey: Down-track location ±25 cm Adv. Sensors Cued: Library match ≥90% using three-criterion metric with equal weighting to the three criteria using first day's IVS inversion as the library item.	Pass – All IVS events achieved a detection offset of <25 cm for all seed items Pass – All IVS events achieved a ≥90% library match using an equally weighted three-criterion match
Complete coverage of the demonstration site	Footprint coverage calculated using UX-Process Footprint Coverage Quality Control (QC) tool; excludes inaccessible areas.	≥85% coverage at 0.75-meter (m) line spacing; and ≥98% coverage at 0.9-m line spacing	Pass – 99.8% coverage was achieved at a 0.75-m line spacing
Along-line measurement spacing	Point-to-point spacing from data set	98% ≤15 cm along-line spacing	Pass – 99.6% of the along-line spacing was ≤15 cm
Detection of all TOI	Percent detected of TOI	100% of TOI detected within 40-cm halo of the surveyed location	Pass – 100% of TOI was detected within a 40-cm halo
Cued interrogation of anomalies	Instrument position	100% of anomalies where the center of the instrument is positioned within 40 cm of actual target location	Fail – only 94% of the cued measurements were within the 40-cm metric
Correctly classify QC seeds and correctly classify native and population seed items	Percent classified as TOI	100% classified as TOI	Pass – all TOI were properly classified
Correctly identify group	Percent of TOI and excavated non-TOI grouped correctly	85% correctly grouped in the small, medium, and large groups	Pass – 97% were assigned to the correct group
Correct estimation of extrinsic target parameters	Measured location and depth-to-center of mass of recovered items	X, Y <15 cm (1 σ) Z <10 cm (1 σ)	Fail – only 67% of X,Y < 15 cm of the actual measured location Fail – only 75% of Z <10 cm of the actual depth
Maximize correct classification of non-TOI	Number of false alarms eliminated	Reduction of clutter digs by >50% while meeting all other demonstration objectives	Pass – 84% of non-TOI were correctly classified
Minimize number of anomalies that cannot be analyzed	Number of anomalies that must be classified as "Unable to Analyze"	Reliable target parameters can be estimated for >95% of anomalies on each sensor anomaly list.	Pass – only 2% classified as "Cannot Analyze"

Table 3.2. Quantitative Performance Objectives for Andersen AFB

Performance Objectives	Metric	Success Criteria	Results
Repeatability of IVS measurements	Amplitude of EM anomaly Measured target locations	Adv. Sensors Survey: Down-track location ±25 cm Adv. Sensors Cued: Library match ≥90% using three-criterion metric with equal weighting to the three criteria using first day's IVS inversion as the library item.	Fail – Two IVS events exceeded the detection offset of <25 cm Fail – Only 87% of cued IVS events achieved a ≥90% library match using an equally weighted three-criterion match. Explanation provided in subsequent sections.
Complete coverage of the demonstration site	Footprint coverage calculated using UX-Process Footprint Coverage QC tool; excludes inaccessible areas.	≥ 85% coverage at 0.50-m line spacing; and ≥ 98% coverage at 0.60-m line spacing	Pass – 93.8% coverage was achieved at a 0.50-m line spacing, 99.1% at 0.60 m line spacing
Along-line measurement spacing	Point-to-point spacing from data set	98% ≤25-cm along-line spacing	Pass – 100% of the along-line spacing was ≤25 cm
Detection of all TOI	Percent detected of TOI	100% of TOI detected within 40-cm halo of the surveyed location	Pass – 100% of TOI was detected within a 40-cm halo
Cued interrogation of anomalies	Instrument position	100% of anomalies where the center of the instrument is positioned within 40 cm of actual target location	Fail – Only 94% of the cued measurements were within the 40-cm metric. Explanation provided in subsequent sections.
Correctly classify QC seeds and native and population seed items	Percent classified as TOI	100% classified as TOI	Pass – all TOI were properly classified
Correctly identify group	Percent of TOI and excavated non-TOI grouped correctly	85% correctly grouped in the small, medium, and large groups	Pass – 98% were assigned to the correct group
Correct estimation of extrinsic target parameters	Measured location and depth-to-center of mass of recovered items	X, Y <15 cm (1σ) Z <10 cm (1σ)	Pass – σ of X,Y offsets <15 cm Pass – σ of Z <10 cm of the actual depth Explanation provided in subsequent sections.
Maximize correct classification of non-TOI	Number of false alarms eliminated	Reduction of clutter digs by >50% while meeting all other demonstration objectives	Pass – 81% of non-TOI were correctly classified
Minimize number of anomalies that cannot be analyzed	Number of anomalies that must be classified as "Unable to Analyze"	Reliable target parameters can be estimated for >95% of anomalies on each sensor's anomaly list.	Pass – only 2% classified as "Cannot Analyze"

4.0 TEST DESIGN

4.1 CONCEPTUAL EXPERIMENTAL DESIGN

Overall, each Live Site Demonstration was conducted with three primary objectives:

1. Correctly classify all TOIs.
2. Reduce clutter digs by at least 50%.
3. Demonstrate the cost and performance of these sensors and methods.

In general, the key components of these demonstrations were:

- Site preparation (i.e., clearing brush, installing seed items, installing IVS).
- Dynamic data collection with advanced sensors (i.e., MetalMapper, TEMTADS 2X2) to detect anomalies.
- Cued data collection with advanced sensors at detected anomaly locations.
- Data analysis and classification to estimate extrinsic parameters (measured location and depths of items).
- Using AGC results to determine a ranked anomaly list.
- Intrusive investigation of selected targets.

Detailed information regarding each site's conceptual experimental design is contained in its respective Final Report. A summary of each site's conceptual experimental design is found in Table 4.1.

Table 4.1. Conceptual Experimental Designs

Project Component	Conceptual Experimental Design	
	Southwestern Proving Ground (SWPG)	Andersen AFB
Site Preparation	▪ 43 seed items installed ▪ Vegetation thinned ▪ IVS installation	▪ 37 seed items installed ▪ Vegetation thinned ▪ IVS installation
Data Collection	▪ 11.23 acres MetalMapper dynamic survey ▪ 2,116 cued surveys	▪ 2.97 acres TEMTADS dynamic survey ▪ 1,195 cued surveys
Data Processing	▪ Processed dynamic and cued data with Geosoft UX-Analyze	▪ Processed dynamic and cued data with Geosoft UX-Analyze
Data Analysis and Classification	▪ Inverted cued results for classification using library matching augmented by visual data review ▪ Dig/No Dig list produced for demonstration analysis	▪ Inverted cued results for classification using library matching and clustering augmented by visual data review ▪ Dig/No Dig list produced for demonstration analysis
Intrusive Investigation	▪ 1,398 target locations intrusively investigated ▪ Each item was photographed and attribute information collected	▪ 243 target locations intrusively investigated

4.2 SITE PREPARATION

Prior to AGC data collection, Weston established sufficient geodetic control points at each site. Vegetation removal was completed when necessary and permissible at each site to allow for quality data collection. Weston UXO technicians performed the surface sweep using handheld analog metal detectors (e.g., Schonstedt® locators) to remove surface metal and any explosive hazards associated with potential MECs. IVS and blind seeds were installed at each site in accordance with the specifications and descriptions contained in *Geophysical System Verification (GSV): A Physics-Based Alternative to Geophysical Prove Outs for Munitions Response* (ESTCP 2009). Test pits were established near the IVS at a quiet location free of subsurface metal and were used to measure the signatures of TOI expected to be present within each demonstration area. Detailed information regarding site-specific preparation is contained in each site's Final Report.

4.3 DATA COLLECTION

4.3.1 Southwestern Proving Ground (SWPG), Arkansas

4.3.1.1 Dynamic Data Collection

Weston performed dynamic detection surveys within the RF-15 demonstration areas April 18–29, 2013. Dynamic detection data were collected from a total of 11.23 acres using the MetalMapper, equating to an average of 1.4 acres per day. Prior to the survey, a map of projected survey lines in RF-15 was loaded into EM3DAcquire to use for navigation. As each survey line was collected, EM3DAcquire displayed a colored swath the width of the sensor footprint showing the operator where data have been acquired. Data gaps were typically identified in the field and re-collected the same day.

The dynamic detection surveys were performed with the MetalMapper sensor seated within a sled, which was attached to the front mount-plate of a diesel-powered tele-lifter (see Figure 4.1). The tele-lifter allowed the MetalMapper to be raised up and down and easily maneuvered side to side. A monitor mounted within the vehicle displayed real-time navigation and sensor information, and allowed the operator to collect data in both dynamic and cued survey modes. EM3DAcquire was used during this demonstration to control data acquisition parameters, storage of data, and navigation.

Figure 4.1. MetalMapper at SWPG

A Trimble® R8 Real Time Kinematic (RTK) GPS was used for navigation. The rover head was mounted directly over the center of the MetalMapper transmit coil. An IMU was installed directly below the rover head to capture pitch, roll, and yaw of the sensor.

Dynamic MetalMapper survey data were acquired with a design line spacing of 0.60 m. Data were initially collected with a 0.75-m line spacing; however, it was observed after the first day of dynamic survey that a 0.75-m spacing was resulting in data gaps because of the soft ground and rutting that was present in the field, so a tighter line spacing of 0.6 m was used to achieve full coverage.

4.3.1.2 Cued Data Collection

Weston performed cued data collection at SWPG May 13–30, 2013, on 2,116 targets that were based on anomaly lists approved by ESTCP, averaging 281 cued locations each day for 8 field days. Cued target locations were loaded into EM3DAcquire, which was used for navigation as well as data storage. The operator positioned the MetalMapper (Figure 4.1) within 40 cm of the center of target location and collected a cued shot for a 60-second period over the anomaly. To account for changing soil conditions, background shots were collected once an hour in a quiet area identified in the dynamic data. The cued data were reviewed each evening, and cued locations that fell outside the 40-cm offset metric were re-collected as necessary.

4.3.2 Andersen AFB, Guam

4.3.2.1 Dynamic Data Collection

Weston performed dynamic detection surveys with the TEMTADS 2x2 using EM3DAcquire to control data acquisition parameters, storage of data, and real-time monitoring of TEMTADS 2x2 sensor and peripheral IMU and RTK data streams. A Trimble R8 RTK GPS was used for navigation. The rover head was mounted directly over the center of the TEMTADS 2x2 array. An IMU was installed directly below the rover head to capture pitch, roll, and yaw of the sensor. Dynamic TEMTADS 2x2 survey data were acquired with a design line spacing of 0.50 m.

Dynamic detection surveys were conducted over the course of five days from January 7–17, 2014. There were a number of no-collection days during this timeframe due to inclement weather as well as TEMTADS 2x2 sensor and computer malfunctions. Dynamic detection data were collected over a total of 2.97 acres using the TEMTADS 2x2, equating to an average of 0.6 acres per day of data collection. Data gaps were typically identified in the field and re-collected the same day to ensure full coverage. Dynamic detection survey using the TEMTADS 2x2 is shown in Figure 4.2. One team member navigates the TEMTADS 2X2 while the other member remotely operates the computer using a tablet and maintains line spacing by placing visual markers (i.e. beanbags).

Figure 4.2. TEMTADS 2x2 at Andersen AFB

4.3.2.2 Cued Data Collection

Weston performed cued data collection over the course of 10 days between January 18 and February 05, 2014, at 1,195 anomaly locations that were based on the approved target lists. Cued data collection averaged 120 cued locations each day during the 10 field days. Cued target locations were reacquired with the RTK GPS and flagged each day prior to data collection. The operator then positioned the TEMTADS 2x2 within 40 cm of the center of the flagged location and collected a cued measurement over the anomaly. To account for changing background conditions, background measurements were collected once per hour in a quiet area identified in the dynamic data set. The cued data were reviewed each evening, and cued locations that fell outside the 40-cm offset metric were re-collected as necessary.

5.0 DATA ANALYSIS AND PRODUCTS

5.1 DYNAMIC DATA PROCESSING

The raw binary AGC .TEM files were converted to American Standard Code for Information Interchange (ASCII) comma-separated value (.CSV) files using data conversion software (i.e., EM3D© or TE^{M2}CSV). Converted data were then imported into Geosoft Oasis montaj for processing and analysis using scripted import routines. Upon import, raw data were inspected to ensure that sensor data were valid and that peripheral input data streams (GPS, IMU) were present. Dynamic detection data were imported, processed, and validated on a daily basis.

The individual sensors within the AGC dynamic detection data were then located and exported to a separately located database, with each sensor assigned a unique version number per line (e.g., Line 1, sensor 1 equates to Line 1.1; Line 1, sensor 2 equates to Line 1.2). Sensor offsets were calculated in reference to the RTK GPS position at the center of the array, with IMU data used to adjust for pitch, roll, and yaw in the sensor array. Data analysis and anomaly selection were performed on the z-axis component of the five innermost receiver cubes (cubes 2–6).

The dynamic detection data were then levelled using a de-median background removal filter. Once the daily data had been imported, validated, and levelled, the data were then merged into a master site database containing all dynamic data collected to date. Once data collection was complete, the master database was used for gridding, anomaly selection, and analysis.

5.2 ANOMALY SELECTION

Anomalies were selected from processed advanced dynamic detection data using the Geosoft Blakely grid peak detection algorithm. To determine a suitable anomaly selection threshold, dynamic test data were acquired over a 20-millimeter (mm) projectile buried at the target detection depth of 15 cm. An example of the 20-mm test strip data collected is shown in Figure 5.1.

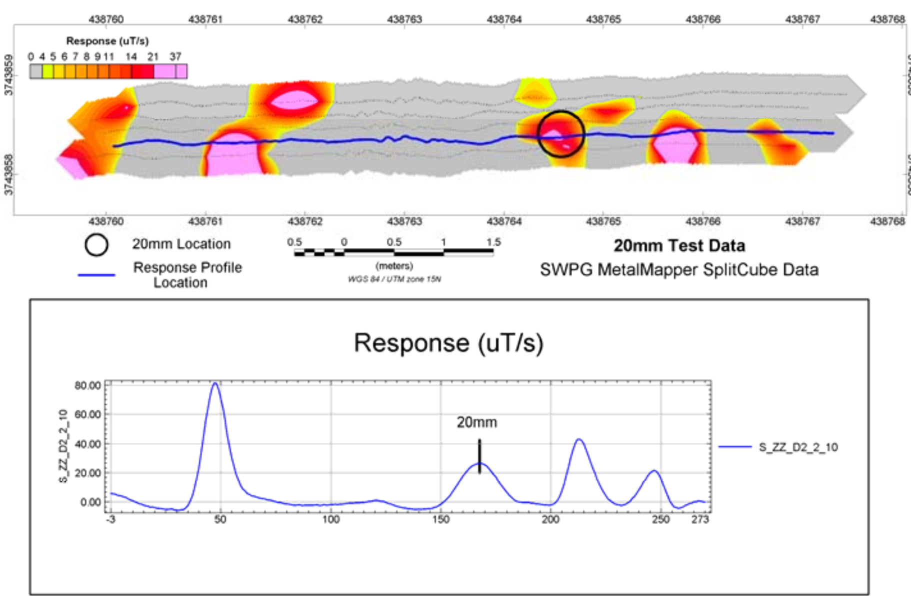

Figure 5.1. 20-mm Dynamic Data Test Strip Response Results

Background noise analyses were performed on anomaly-free locations within the test strip data. A target conservative threshold of 7 times the root mean square (RMS) noise level was chosen to allow the detection of a 20mm projectile at a depth of 15 cm below ground surface.

5.3 CUED DATA PROCESSING

Cued data processing was performed using the UX-Analyze Advanced extension in Geosoft Oasis montaj. Cued background data were imported and qualitatively verified, with any outliers removed from the background dataset. After background data had been verified, cued anomaly data were imported, verified for completeness, and background corrected using the cued background data spatially and temporally closest to the cued anomaly location.

Inversions were performed on each cued anomaly using both single-source and multi-source models to extract target parameters, fit coherence, and predict locations and depths for each model. The primary parameters used for classification were the three polarizabilities (β_1, β_2, and β_3) calculated for each single-source and multi-source modeled result.

Daily quality control (QC) was performed on the cued anomaly data in which the cued location (RTK GPS location), modeled locations, and flagged locations were compared to verify that the center of the AGC sensor array was within the 40-cm radius of the anomaly source. Targets outside the 40-cm metric were identified and re-collected as necessary.

After the individual inverted locations from the cued sensors were complete, the data were combined into a Master Dig List for each anomaly group. These Master Dig Lists contained one entry for each predicted anomaly from the inversions of the cued data.

6.0 PERFORMANCE ASSESSMENT

This section discusses the performance assessments for AGC sensors at each of the sites. A summary of the performance objectives and results for each demonstration project are located in Section 3, Table 3.1 (SWPG) and Table 3.2 (Andersen AFB) of this report. Detailed information regarding each site's performance assessment results is contained in its respective Final Report.

6.1 REPEATABILITY OF IVS MEASUREMENTS

This objective involved the repeatability of the detection location and classification (cued data) of seed items in dynamic IVS data collection. Seed item offsets for each dynamic IVS data collection event, and library match statistics for each cued IVS data collection, were tracked throughout the life of the dynamic portion of the project. This objective for dynamic collection was considered to be met if all locations of seed items as detected in the IVS data were offset <25 cm from the actual surveyed location. This objective for cued collection was considered to be met if the library match statistic for all seed items cued in the IVS was ≥90% when using a three-criterion metric with equal weighting to the three criteria when measured against the first day's cued IVS. These performance objectives for both dynamic and cued data were met at SWPG.

At Anderson AFB, the dynamic metric of 25 cm was exceeded on two occasions, therefore, the dynamic metric was not met. The cued metric was not met because not all of the library match statistics were >90% during the duration of the cued survey. The exact source of the failures were not determined, however a contributing factor was most likely the IVS construction or the seed items installed in the IVS. Due to limited suitable space available to install an IVS within the North Ramp Parking (NRP) area, the existing IVS established for the EM61-MK2 survey being performed in support of the clearance activities was used for the demonstration. Schedule 40 Industry Standard Objects (ISOs) were used in the IVS, which may have been a contributing factor to the inconsistent results of the deeper small ISO seed item IVS03. It is unclear what caused the match statistic deviations over the medium ISO seed items. To assess data usability, production data were evaluated from any day that IVS deviations were observed, and no indications of a system failure with respect to data usability were observed. Seed items cued during the days in question were properly classified with high confidence statistical matches, and no deficiencies were noted in sensor performance.

6.2 COMPLETE COVERAGE OF THE DEMONSTRATION SITE

This objective measured the effectiveness of the dynamic detection survey as a function of the amount of coverage of the demonstration area by the AGC sensor. This objective was considered to be met if the dynamic detection survey achieved its instrument-specific objective when analyzed using the UX-Process Footprint Coverage QC tool.

At SWPG, the UX-Process Footprint Coverage QC tool was used to analyze the georeferenced positions of the center of the AGC sensor array. Data were collected at a 0.50-m line spacing to eliminate gaps caused by ruts and rough terrain. This objective was met because 99.8% of the site was covered at a 0.75-m line spacing.

At Andersen AFB, the UX-Process Footprint Coverage QC tool was used to analyze the georeferenced positions of the center of the TEMTADS 2x2 sensor array. Data were collected at a 0.50 m line spacing to eliminate gaps caused by ruts and rough terrain. This objective was met, as 93.8% of the site was covered at a 0.50 m line spacing, and 99.1% at 0.60 m line spacing.

6.3 ALONG-LINE MEASUREMENTS

This objective evaluated the along-line data density, or sample separation, of the TEMTADS 2x2 dynamic detection dataset acquired within the NRP area. The metric for this objective was the point-to-point distance as measured using the UX-Process Sample Separation utility.

At SWPG, this objective was considered to be met if 98% of the data had an along-line spacing of 15 cm or less. The UX-Process Sample Separation tool was used to analyze the along-line spacing of the georeferenced data positions of the MetalMapper sensor array. This objective was met because 99.6% of the data had a sample separation of 15 cm or less.

At Andersen AFB, this objective was considered to be met if 98% of the data had an along-line spacing of 25 cm or less. The UX-Process Sample Separation tool was used to analyze the along-line spacing of the georeferenced data positions of the TEMTADS 2x2 sensor array. This objective was met, because 100% of the data had a sample separation of 25 cm or less.

6.4 DETECTION OF ALL TOI

This objective evaluated the dynamic detection capabilities of the AGC sensors. The metric for this objective was considered to be met if 100% of native and non-native TOI were detected within a 40-cm halo of their recorded locations. Non-native TOI within these demonstration areas included a combination of blind seed items, which were completely blind to the data collection and processing teams, as well as QC seed items for which the locations were known.

At SWPG, this objective was met because all TOI were successfully detected within 40 cm of the recorded locations. TOI included 43 seed items (non-native TOI) installed by Weston prior to the dynamic detection survey, as well as 1 MEC item (native TOI). The average seed time offset for this investigation was 10.25 cm.

At Andersen AFB, this objective was met because all TOI were successfully detected within the TEMTADS 2x2 dataset within 40 cm of the recorded locations. TOI included 19 seed items (non-native TOI) installed by Weston prior to the dynamic detection survey. The average seed item offset for this investigation was 10.2 cm.

6.5 CUED INTERROGATION OF ANOMALIES

This objective evaluated the positioning of the instrument during data collection in relation to the actual anomaly location. The metric for this objective was considered to be met if the center of the instrument was positioned within 40 cm of the actual anomaly location for 100% of the cued anomalies. To evaluate this objective, the offset between the center of the AGC sensor array and the surveyed location of each recovered item was calculated.

At SWPG, this objective was not achieved because only 94% of the cued measurements were within the 40-cm offset. Of the 1,398 cued measurements that were intrusively investigated, 1,301 were within the 40-cm offset metric, and 86 were outside of 40 cm. The remaining 11 reacquired anomalies were determined to be no-contacts and were removed from this evaluation.

At Andersen AFB, this objective was not achieved because only 94% of the cued measurements were within the 40-cm offset. Direct comparison of TEMTADS 2x2 cued locations to the actual location of recovered items is not possible. Detailed intrusive information and locations of recovered items were not collected by the contractor performing the MEC removal activities. As a result, this objective was evaluated by comparing the offset between the center of the TEMTADS 2x2 array and the fit location of each source. Of the 1,195 cued measurements that were analyzed, 1,127 were within the 40-cm offset metric, and 68 were outside of 40 cm. Of the 68 cued measurements that were outside of 40 cm, 39 of these exceedances were from the 977 targets (4% of TEMTADS targets) selected from dynamic TEMTADS 2x2 data, and 29 were from the 218 targets (13% of the EM61 targets) selected from EM61-MK2 data. The increased exceedance rate at targets selected from the lower resolution EM61-MK2 dynamic detection survey suggests that the data from which the target locations are selected will influence failure rates.

6.6 CORRECTLY CLASSIFY QC SEEDS

This objective evaluated the effectiveness of the advanced classification process to properly classify TOI present within the survey area. The objective was considered to be met if 100% of the QC seeds, population seeds, and native TOI were placed on the TOI list.

At SWPG, a ranked anomaly list was submitted to the ESTCP Program Office for evaluation. This objective was met, because all TOI were properly classified as Category 1 digs (likely TOI). This listing included one 105mm projectile (MEC) recovered in Anomaly Group 1.

At Andersen AFB, a ranked anomaly list was submitted to the ESTCP Program Office for evaluation. This objective was met, because all TOI were properly classified as Category 1 digs (likely TOI).

6.7 CORRECTLY IDENTIFY GROUPS

This objective evaluated the effectiveness of the advanced classification process to properly assign each excavated TOI and non-TOI into the small, medium, or large grouping. The objective was considered to be met if 85% of the anomalies placed on the dig list were properly grouped. Dig results for the ranked anomaly list submitted to the ESTCP Program Office were analyzed to verify size groupings.

At SWPG, of the 195 anomalies placed in the dig list, 190 were assigned to the correct size group, and 5 were assigned an incorrect group. This objective was met because 97% of the anomalies were correctly classified.

At Andersen AFB, intrusive investigations were performed to the specifications of the third-party contractor’s work plan, and did not follow the standard ESTCP intrusive investigation requirements, so dig data obtained did not include precise locations, depths, photos, or descriptions of items recovered. Since precise data were not available, a qualitative analysis was performed on the dig results to determine if the proper group was assigned to each item.

Of the 220 anomalies placed on the dig list, 186 were assigned to the correct size group, 3 were assigned an incorrect group, and 31 did not have adequate data to make a comparison. This objective was met, as 98% of the anomalies that had adequate dig data for a qualitative comparison were correctly classified.

6.8 CORRECT ESTIMATION OF EXTRINSIC TARGET PARAMETERS

This objective evaluated the accuracy of the target parameters that were estimated during the data inversion process by comparing the predicted extrinsic target parameters to the measured results recorded during the intrusive investigation. This objective was considered to be met if the estimated X and Y locations were within 15 cm and the estimated depths were within 10 cm.

At SWPG, this objective was not met because only 67% of the predicted locations were within 15 cm of the actual measured location, and only 75% of the predicted depths were within 10 cm of the actual depths. The high percentage of item locations that were not predicted correctly was most likely a result of the quantity of frag that was encountered within the survey area. Approximately 97% of the digs resulted in small pieces of frag that were either too numerous or too small to model well, thus yielding poor fit locations.

At Andersen AFB, detailed locations and depths of items recovered were not recorded during the intrusive investigation, so a complete evaluation of all cued data could not be performed. Therefore, this objective was evaluated by comparing the fit locations derived from the cued TEMTADS data to the RTK surveyed locations and depths of the seed items installed within the TEMTADS demonstration area. Based on that assessment, this objective was met, as the standard deviation for each of the X and Y horizontal offset and the Z vertical offset were <15 cm and <10 cm, respectively.

6.9 MAXIMIZE CORRECT CLASSIFICATION OF NON-TOIs

This objective concerns the component of the classification problem that involves false alarm reduction. The metric for this objective is the number of cued anomalies that can be correctly classified as non-TOI. The objective was considered to be met if we were able to reduce clutter digs by >50% while meeting all other demonstration objectives. Dig results for the initial ranked anomaly list submitted to the ESTCP Program Office were used to assess the number of non-TOI that were correctly classified.

At SWPG, this objective was met because 84% of non-TOI were correctly classified. In this classification scenario, 100% of TOI were correctly classified while achieving a false positive rate of only 15%.

At Andersen AFB, this objective was met because 81% of non-TOI were correctly classified. In this classification scenario, 100% of TOI were correctly classified while achieving a false positive rate of only 18%.

6.10 MINIMIZE NUMBER OF ANOMALIES THAT CANNOT BE ANALYZED

This objective evaluated how well the modeled results of the inversion process correlated to the observed data. A fit coherence metric was calculated for each model during data inversion, and was used as the basis for determining whether reliable parameters could be estimated from the data. Modeled results with a fit coherence of <0.8 were placed in the 'cannot analyze' category. The objective was considered to be met if reliable parameters could be estimated for >95% of the anomalies on each sensor anomaly list.

At SWPG, this objective was met because 98% of the cued data collected inverted with a fit coherence >0.8.

At Andersen AFB, this objective was met because 98% of the cued data collected inverted with a fit coherence >0.8.

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7.0 COST BENEFIT ANALYSIS

This cost assessment for the SWPG and Andersen AFB demonstrations includes a summary list of the project costs and potential savings from the classification process.

7.1 COST SUMMARY

Tables 7.1 and 7.2 present a cost summary for the technology used at each demonstration site for this project.

Table 7.1. Details of Project Costs, SWPG

Phase of Work	Elements of Work	Estimated Costs
Site Setup	Site prep, surface sweep, seeding, IVS installation	$81,109
Dynamic Detection Survey	Includes effort for field data collection and processing/anomaly selection	$52,241
Cued Survey	Equipment	$13,500
	Cued data collection	$34,583
	Processing and classification	$22,730
	Total cost per target for cued survey	$33.46/target for 2,116 targets
Intrusive Investigation	Intrusive investigation of 1,398 anomalies, reacquire, demo operations, and related costs	$195,860
	Total cost per target to intrusively investigate	$140.10/target for 1,398 targets

Table 7.2. Details of Project Costs, Andersen AFB

Phase of Work	Elements of Work	Estimated Costs
Mobilization/Demobilization	Travel for a geophysicist and UXO technician and shipment of TEMTADS 2x2 and other equipment	$16,000
Site Setup	Site prep, seeding, IVS installation, weather delays	$15,000
Dynamic Detection Survey	Includes effort for field data collection (2.97 acres), equipment, expenses, labor for geophysicists and UXO technicians, processing/anomaly selection, weather delays/downtime and local subcontractor support (10 days)	$34,000
	Total cost per acre for dynamic survey	$11,447/acre
Cued Survey	Equipment, data collection, labor for geophysicists and UXO technicians and expenses, weather delays/downtime, and local subcontractor support (5 days)	$51,000
	Data processing and classification	$34,000
	Total cost per anomaly for cued survey	$71/anomaly for 1,195 anomalies

7.2 COST DRIVERS

This analysis presents and compares the costs of the dynamic and cued surveys to the outcome of the classification process.

During the SWPG demonstration, 2,116 targets were surveyed in cued mode with MetalMapper. Based on the information listed in Table 7.1, the cost for the cued survey and classification was $33.46 per target. Of these 2,116, a total of 1,398 were intrusively investigated at a cost of $140.10 per target.

During the Andersen AFB demonstration, a total of 2.97 acres of dynamic detection survey data was collected using TEMTADS 2x2 over the course of 10 days. The total cost for the dynamic detection survey was approximately $34,000 equating to $11,447 per acre. The cued survey, data analysis, and classification at 1,195 anomalies totaled $85,000 equating to $71 per anomaly.

Due to logistical considerations with the location of Guam, travel (mobilization/demobilization) as well as site setup are separately reported in Table 7.2. Weston also procured the help from a local subcontractor to provide additional UXO technician escort and avoidance support, vehicles, storage, and equipment. TEMTADS 2x2 shipping was approximately $12,000. Expenses and some labor were expended during weather delays and downtime due to equipment issues.

Weston considers the costs incurred for each AGC demonstration and intrusive investigation an overestimation of the actual costs that would be necessary for future projects because these costs included equipment delivery delays, significant logistical considerations, and lengthy setup and orientation processes. In addition, these AGC demonstration sites required additional efforts.

7.3 COST BENEFIT

During the SWPG demonstration, cued surveys and processing were performed for $33.46 per target, and intrusive investigation was performed for $140.10 per target. The classification process eliminated 83% of anomalies from the intrusive investigation, yielding a potential cost savings on this project of $114,898.00, based on the following factors:

- 1,398 anomalies at $140.10/anomaly for intrusive investigation equals approximately $195,860.
- Reduction of 1,154 anomalies equals a reduction of $161,675 in excavation costs.
- MetalMapper cost for cued survey and classification of 1,398 anomalies at $33.46/ anomaly equals a cost of $46,777.
- Total cost savings under this scenario equals $114,898.

During the Andersen AFB demonstration, cued surveys and processing were performed for $71.00 per target, and intrusive investigation was performed for $150.00 per target. The classification process eliminated 81% of anomalies from the intrusive investigation, yielding a potential cost savings on this project of $57,955, based on the following factors:

- 1,195 anomalies at $150.00/anomaly for intrusive investigation equals approximately $179,250.

- Reduction of 952 anomalies equals a reduction of $142,800 in excavation costs.
- TEMTADS 2X2 cost for cued survey and classification of 1,195 anomalies at $71.00/ anomaly equals a cost of $84,845.
- Total potential cost saving under this scenario equals $57,955.

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8.0 IMPLEMENTATION ISSUES

Several implementation issues arose during the AGC demonstrations, such as equipment shipping logistics, software malfunctions, broken cables caused by cattle, and site accessibility issues because of heavy rains causing flooded site conditions. These types of setbacks are typical of any site and should be expected when planning field operations. Weston discussed suggested improvements to the system with Geometrics once survey operations were completed, to include the following:

- **Simplify the cables** – One of the more time-consuming aspects of dealing with MetalMapper is cable management. Each of the receivers and transmitters needs to be individually attached and secured. Weston suggested that the cables be reduced to a single "transmitter" cable and a single "receiver" cable.

- **Weatherproof the system** – Limited protection of cables and electronics is built into the AGC systems. On the MetalMapper, the computer sits facing up, with no shield to protect it from rain/debris/dust. Most of the cables do not have any additional sheathing beyond the manufacturing minimum, making them prone to pinches and pulls. On the TEMTADS system, the clamshell is not sealed from outside moisture and dust. Sensor failures, likely due to moisture entering the clamshell, resulted in several days of downtime and system troubleshooting. A rubber gasket to seal the top and bottom clamshell pieces, as well as the cable harness entering the clamshell, is a possible solution.

- **Structural improvement** – Several components of the MetalMapper require structural improvements. The GPS needs to be redesigned for additional stability and less maintenance (replacing screws/nuts that are consistently coming loose). The cushions used for vibration dampening need to better adhere to the MetalMapper or be integrated into the instrument design. The basket that holds the computer should be adjusted in size so that it actually holds the computer. Currently, a combination of duct tape and come-along straps are used to secure the computer in place on the sled.

- **Wheels –** Currently the TEMTADS wheels are held on by zip ties, as opposed to nylon bolts or cotter pins. These zip ties failed on almost a daily basis, leading to downtime to reattach wheels and re-collect affected lines.

- **Tow versus push sled design** – The MetalMapper sled is currently constructed to be "pushed" during survey. For the cued investigation, this setup is ideal because it allows the user greater control and visibility when moving the sensor into a specific location. For the dynamic survey, a towed sled might be a better option, depending on the terrain. The installation of a ball-hitch on the sled would allow the user to have a choice in the field and potentially increase the versatility of the instrument.

- **Other modifications** – Other modifications discussed included a touchscreen interface for data collection, altering the color schemes of the software for greater visibility, and altering data-file nomenclature for easier data management. In addition, a modification of EM3DAcquire is suggested to allow for display of dynamic data collection progress (plot tracks on map, similar to MetalMapper EM3D interface) and the option to import a flag/target list into TEMDatalogger to avoid operator input errors.

9.0 REFERENCES

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